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The Starfish southern conjugate rebrightening is explained by velocity diffusion perpendicular to the earth's magnetic field line. The diffusion is caused by particle scattering off of the harmonics of ion cyclotron waves commonly called Bernstein modes. Quasilinear estimates of the wave fluctuation levels indicate that the debris streaming down the field lines will excite these waves and then be scattered by them.

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QUASILINEAR SCATTERING FROM WAVES DRIVEN BY BEAM-PLASMA INSTABILITIES

INTRODUCTION

Test data taken during the Starfish event of 1962 displays a marked second brightening of the atmosphere in the southern conjugate region. This brightening followed the initial luminescence in the southern conjugate region caused by the deposition of the initial debris by approximately 10 seconds.

The explanation that appears most probable involves scattering a fraction of the streaming debris out of the loss cone as the debris proceeds toward the southern conjugate region. The scattering sources are waves excited to high levels driven by the initial fast debris. The scattered debris would then mirror in the southern conjugate and stream toward the magnetic bubble. Some fraction would be scattered back into the loss cone region by the loss cone instability. The remainder would mirror off of the bubble and return toward the southern conjugate region. During the return the loss cone region could be filled by loss cone instabilities and a second precipitation of debris particles could occur. The second precipitation would involve a greater proportion of the distribution because of nonlinear flattening of the distribution function.

Manuscript submitted March 3, 1980

In this report the possibility of exciting the waves which are predicted to perform the scattering is addressed. It will be shown by use of a numerical code and quasilinear estimates that indeed waves can be excited and will grow to sufficient levels to cause quasilinear diffusion of the streaming debris distribution function.

The code employed is a linear code which has been used to study beam-plasma instabilities in tokamaks. The circumstances of the problem are similar to a beam-plasma interaction, the general type of which, have been studied for a number of years in the fusion community.[1-5] The linear code calculates the energy transfer between the beam and waves of interest and the waves with the background plasma to determine the growth rates and energy transferred to the wave. From these calculations quasilinear estimates are made to determine the amount of scattering taking place.

There are a large number of waves which may be excited by a beam of high energy ions.[4] Among them are the ion cyclotron wave, ion Bernstein wave, ion acoustic wave, low-hybrid waves and shear Alfven waves. Several of these waves are of high frequency and candidates for study. However, the ion cyclotron wave and its higher harmonics, usually called the ion Bernstein wave, are chosen for study because these waves have been predicted theoretically[1] and shown experimentally[6-10] to be excited during beam plasma interactions. The code employed for this work was successful in predicting quite accurately these instabilities in a variety of plasma devices from Q machines, to Tokamaks such as the French tokamak, TFR,[10] and PLT, the Princeton Large Torus.

In the following section the details for calculating the linear growth rates for the waves will be briefly discussed. The quasilinear estimates are presented in the following section and finally the conclusion of these calculations are presented.

LINEAR CALCULATION

The linear calculation is based on a perturbation method where the real frequency is assumed larger than the imaginary, $\omega_r > \omega_i$.[4,11] The code calculates the rate of change of the wave energy by computing a time averaged $\underline{J} \cdot \underline{E}$ for each species given by the following formula

$$\frac{dW_k}{dt} = \langle \underline{J} \cdot \underline{E} \rangle \equiv \sum_j L_j \equiv \sum_j n_j \mathcal{L}_j \tag{1}$$

where the sum j is over the plasma species. Physically the process of energy transfer takes place through resonant processes either Landau cyclotron or anomalous cyclotron resonances. The beam transfers energy to the wave and background plasma. The wave in turn transfers energy to the background electron or ions. If the beam pumping rate is larger than the damping rates the wave grows.

Typically, the instability is parameterized by the amount of beam density necessary to drive the wave unstable, n_b. From Eq. (1) a marginal stability criterion can be established. For marginal stability

$$n_i \mathcal{L}_i + n_e \mathcal{L}_e + n_b \mathcal{L}_b = 0 \tag{2}$$

where n_j are the densities of the species and $\mathcal{L}_j$ is the power transferred per particle. One then obtains

$$\left(\frac{n_b}{n_e}\right)_{\text{critical}} = -\frac{\mathcal{L}_e + n_i \mathcal{L}_i / n_e}{\mathcal{L}_b} \tag{3}$$

and

$$\gamma = \frac{1}{2W_k}\frac{dW_k}{dt} = \frac{n_e \mathcal{L}_b}{W_k}\left(\frac{n_b}{n_e} - \left(\frac{n_b}{n_e}\right)_{crit.}\right) \tag{4}$$

where Eq. (4) is the equation for the growth rate. If n_b is known then the code calculates the power transfer per particle for the beam, $\mathcal{L}_b$, and the wave energy for the wave being studied to produce the growth rate. Obviously if $n_b/n_e < (n_b/n_e)_{crit.}$ the mode is damped. The power transfer function is calculated from the following formulas;[1,4]

$$\mathcal{L}_j = \frac{-e^2 Z_j}{4|k_{||}|v_j^3 m_j} \sum_{\ell=-\infty}^{\infty} |M_j^\ell| \varepsilon_j^\ell \tag{5}$$

where

$$M_j^\ell = \frac{\ell\omega_{cj} E_\perp}{k_\perp} + \frac{\omega - \ell\omega_{cj}}{k_{||}} E_{||} \tag{6}$$

and

$$\varepsilon_j^\ell = 4\pi^2 \int_0^\infty dv_\perp v_\perp J_\ell^2\left(\frac{k_\perp v_\perp}{2\omega_{cj}}\right)\left[\left(1 - \frac{\ell\omega_{cj}}{\omega}\right)\frac{\partial F_j}{\partial v_{||}^2} + \frac{\ell\omega_{cj}}{\omega}\frac{\partial F_j}{\partial v_\perp^2}\right]_{v_{||} = c_j^\ell} \tag{7}$$

with

$$c_j^{\ell} \equiv (\omega - \ell\omega_{cj})/k_{||}$$

For Maxmillian Species

$$\mathcal{L}_{j=e,i} = \frac{Z_j^2 e^2}{2|k_{||}|v_j^3 m_j} \sum_{\ell=-\infty}^{\infty} |M_j^{\ell}|^2 I_{\ell}(b)\bar{e}^{b} e^{-(\omega - \ell\omega_{cj})^2/k_{||}^2 v_j^2} \tag{8}$$

where I(b) is the modified Bessel function, $b = \frac{1}{2}\left(\frac{kv}{\omega_{cj}}\right)^2$ and $v_j = \left(2T_j/m_j\right)^{1/2}$.

As can be seen from Eq. (7) in order to perform the calculations one needs to know the distribution function for the beam, F_b. One could assume a monoenergetic beam of particles streaming down the field lines but while such a distribution will produce unstable waves it does not appear realistic.

Noting that the debris streaming down the field lines has already interacted with the coupling shell through a variety of instabilities, i.e., loss cone and mirror instabilities, one needs a more sophisticated model. The model must also consider the effects of velocity dispersion because the excitation of the scattering wave can occur at considerable distances from the burst point. For a simple model of these effects one can use the Fokker-Planck Equation[1] to obtain a distribution which will represent the fact that the debris particles have been scattered in velocity space. Inclusion of a source term in the Fokker-Planck equation

allows one to model the velocity dispersion. That is, particles are introduced into velocity space at a given location. The results of running the Fokker-Planck section of the code is shown in Figure 1. The beam was injected at 200 keV or a velocity of 1.18×10^8 cm/sec. The distribution was allowed to evolve until an appropriate spread in velocity was obtained. As can be seen in Figure 1 the resulting distribution function the particles have a pitch angle ratio of about 10 to 1, $V_{||}$ to $v_{\perp}$, consistent with the mirror ratio of the magnetic bubble. In addition, the particle density is weighted toward the high velocity side which is the effect produced by velocity dispersion along the magnetic field line. The slow edge of the distribution has a parallel velocity near 7.3×10^7 cm/sec.

This distribution while not having the exact details of the debris distribution function appears to have the quantitative details which are of interest. In the calculations to be discussed, this is the distribution employed. It represents, we feel, a conservative estimate due to the smoothness and the way we introduced the beam. Only one-quarter of the actual beam density was obtained so the actual gradients are in fact smaller than might be expected.

It should be noted that the effect of the velocity dispersion is very important because the instability grows in the positive slope region of the instability. This characteristic has a definite effect in determining where the velocity will be excited and what part of the total debris spectrum will be affected. These effects will be discussed later in this report.

Upon running the linear code it was found that, while the fundamental electrostatic mode of the ion cyclotron wave could be excited, very little energy was transferred into this mode. Therefore growth rates were quite small and insufficient for the anticipated pulse width of the debris. The details of the dispersion relation for the ion cyclotron wave and its higher harmonics, the ion Bernstein waves, can be found in Reference [1].

It was found that the ion Bernstein waves could be excited with quite large growth rates. These rates approached the real frequency of the mode when n_b was taken to be 20% of n_e. The parameters used for these calculations are shown in Table I. Two harmonics of the wave were considered. In the first wave to be studied the second cyclotron harmonic of the beam cyclotron frequency resonantes with the wave near the second harmonic of the plasma cyclotron frequency, i.e.,: $\ell\omega_{cb} \simeq \ell\omega_{ci}$ where $\ell_b = \ell = 2$. In the case of exciting the third harmonic of the ion Bernstein mode the resonate match was $\ell_b = 2$, $\ell = 3$.

Both waves were found to be easily excited because the resonant nature of the modes minimizes the Landau and cyclotron damping of the modes. There was considerable energy transfer from the beam to the wave and the growth rates approached $\ell\omega_{ci}$, the limits of the code. Table II show typical results of the second harmonic calculation. It can be seen from Table II that the typical scale for the wavelengths are about 6 km in the perpendicular direction and 30 km in the parallel direction. The group velocities appear to be slow enough so that the excitation process will occur on time scales faster than the energy transport. In summary

the results from the linear calculations indicate that waves of the ion Bernstein type will be excited and so will some of the higher frequency waves.

QUASILINEAR CALCULATION

In this section the quasilinear estimates for the pitch angle scattering of the streaming debris are addressed. The purpose of this discussion is to ascertain whether or not quasilinear effects would be important. It should be noted from the outset that to perform this calculation with complete accuracy one needs to do the problem numerically in two dimensions. However, the approximation to one dimensional diffusion is reasonably good as the perpendicular electron field of the wave, $E_\perp$, is considerably larger than the parallel $E_{||}$, $E_\perp >> E_{||}$. The general approach for quasilinear calculations can be found in Reference 12.

As mentioned, the waves being considered are electrostatic in nature. This allows one to write the equation for the quasilinear behavior of the beam distribution as

$$\frac{\partial f_b}{\partial t} = \pi \left(\frac{e_b}{m_b}\right)^2 \sum_{k_{||}k_\perp} \left(k_{||}\frac{\partial}{\partial v_{||}} + \frac{\ell\omega_{cb}}{v_\perp}\frac{\partial}{\partial v_\perp}\right) |\phi_k|^2 \, \delta\left(\omega - \ell\omega_{cb} - k_{||}v_{||}\right)$$

$$\times J_\ell^2 \left(k_\perp v_\perp/\omega_{cb}\right) \left(k_{||}\frac{\partial f_b}{\partial v_{||}} + \frac{\ell\omega_{cb}}{v_\perp}\frac{\partial f_b}{\partial v_\perp}\right), \tag{9}$$

where J_ℓ is the Bessel function and ϕ_k is the electrostatic potential. For the unstable modes the parallel wave electric field is sufficiently small that the quasilinear diffusion reduces to a diffusion in $v_\perp$ at a constant $v_{||}$ given by

$$\frac{\partial f_b}{\partial \tau}\bigg|_q = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left[v_\perp D(v_\perp, v_{||})\right]\frac{\partial f_b}{\partial v_\perp} \sim \frac{f_b}{\tau_q} , \qquad (10)$$

where

$$D(v_\perp, v_{||}) = \frac{\pi e_b^2}{m_b^2}\left(\frac{\ell\omega_{cb}}{v_\perp}\right)^2 \sum_k |\phi_k|^2 J_\ell^2\left(\frac{k_\perp v_\perp}{\omega_{cb}}\right) \delta\,(\omega_k - \ell\omega_{cb} - k_{||}v_{||}) \;. \qquad (11)$$

Equation (10) defines the quasilinear time, i.e., the time scale upon which one expects quasilinear affects to act. The sum over the resonant modes is related to the sum over the fluctuation spectrum through the correlation time given by $\tau_c = 1/\Delta k_{||}v_b| = (\Delta v_{b||}/v_{b||}\delta\omega)$ where $\Delta v_{b||}/v_b$ is the relative width of the parallel velocity distribution and $\delta\omega = \omega - \ell\omega_{ci}$. This time scale is a measure of the time the beam will stay in resonance with the wave. Although the time τ_c can be long compared to the wave period, one finds that the quasilinear conditions remain valid for the noise levels estimated here for many e-folding times.

One can define the ratio of rf wave energy density to the thermal plasma density by

$$\Gamma_{rf} = \frac{W_k}{\frac{3}{2}\left(n_e T_e + n_i T_i\right)} \tag{12}$$

where the wave energy, W_k, is defined in Reference 1 as

$$W_k \sim \frac{2\omega_{pi}^2}{k_\perp^2 v_i^2}\left(\frac{\ell\omega_{ci}}{\omega - \ell\omega_{ci}}\right)^2 \frac{I_\ell(b)e^{-b}}{16\pi}\,|E_k|^2 \;, \tag{13}$$

where $b \equiv \left(\frac{k_\perp v_\perp}{\omega_{ci}}\right)^2/2.$

For this case $E_k = E_\perp$ and it is assumed that $T_e = T_i = T$ for the rest of the calculation. Substituting Eq. (13) into Eq. (12) returns the following expression

$$\Gamma_{rf} = \frac{1}{12}\sum_k \left|\frac{e\phi}{T}\right|^2 \frac{(\ell\omega_{cb})^2}{(\omega - \ell\omega_{cb})^2}\; I_\ell(b)e^{-b} \;. \tag{14}$$

Using Eqs. (10) and (11) as well as the correlation time leads to the expression for the quasilinear time

$$\frac{1}{\tau_q} \sim \frac{\pi e_b^2\, v_{b||}}{m_b^2\,\Delta v_{b||}\,\Delta v_{b\perp}^2\, v_{b\perp}^2}\,\frac{(\ell\omega_{cb})^2}{(\omega - \ell\omega_{cb})}\; J_\ell\!\left(\frac{k_\perp v_\perp}{\omega_{cb}}\right)\sum_{k_\perp} |\phi_k|^2 \;. \tag{15}$$

From Eqs. (14) and (15) one obtains the final form for the quasilinear time

$$\frac{1}{\tau_q} = 3\pi\omega_{cb}\Gamma_{rf}\left(\frac{T}{E_b}\right)^2 G_b \frac{\omega - \ell\omega_{cb}}{\omega_{cb}} \frac{J_\ell^2\,(k_\perp v_\perp/\omega_{cb})}{I_\ell(b)\bar{e}^{b}} e^{2\gamma t} , \qquad (16)$$

where

$$G_b \equiv V_b^4\, v_{b||}/v_{b\perp}^2\, \Delta v_{b||}\, \Delta v_{b\perp}^2$$

measures the localization of the fast ion distribution velocity space. It is assumed that the fluctuation potential begins from thermal levels therefore W_k (thermal) = $(2\pi)^{-3}$ T Δ^3 k and using Eq. (13) the electric field at the thermal level is estimated to be

$$E_\perp^2 = \frac{T\,\Delta^3 k\ 16\pi(\omega - \ell\omega_{ci})^2}{I_\ell(b)\bar{e}^{b}\ell^2\omega_{pi}^2}\ e^{2\gamma t_o},\ t_o = 0 . \qquad (17)$$

One last relation must be determined, that is the growth time necessary for the mode to grow to nonlinear or saturated levels. This can be estimated by recalling that trapping effects will occur when the noise level has grown sufficiently. Typically this would occur when the trapping velocity $(e\tilde{\phi}/m_b)^{1/2}$ becomes equal to $\Delta v_{b||}$ or equivalently when the resonant fast ion bounce frequency, $k_{||}(e\phi/m_b)^{1/2}$, becomes equal to the decorrelation rate $1/\tau_c$. Applying this condition to Eq. (14) one arrives at the relation

$$\Gamma_{rf}(\text{trap}) \sim \frac{1}{12}\left(\frac{\Delta v_{b||}}{c_s}\right)^4 \left(\frac{\ell\omega_{cb}}{\omega - \ell\omega_{cb}}\right)^2 I_\ell(b)e^{-b} \tag{18}$$

with c_s defined as the sound speed. At this point one can estimate the time it will take the mode to encounter nonlinear effect with the relation,

$$\tau_s \sim \frac{1}{2\gamma}\,\ell n\left(\frac{\Gamma_{rf}(\text{trap})}{\Gamma_{rf}(\text{thermal})}\right) . \tag{19}$$

Using the values contained in Tables I, II, and III, Eqs. (16) and (19) can be evaluated. The quasilinear time estimate and the trapping time estimate can be compared to one another and with the correlation time to determine if the quasilinear effects have been self-consistently estimated.

Equations (16) and (19) along with the relation for the correlation time were numerically evaluated. The correlation time, τ_c, was found to be in the range of 0.025 to 0.1 sec. This implies that the positive slope of the distribution function such as shown in Figure 1 will be resonant with the wave for times of order 0.1 sec. The quasilinear time, τ_q, which is the measure to determine if strong pitch angle scattering will occur on a time scale comparable with or faster than the correlation time, is found to be on order 10^{-3} sec after the perturbed potential has grown for $\sim$0.05 to 0.1 sec. The higher harmonic modes reach the point of rapid quasilinear diffusion in shorter periods. Finally, the saturation time, τ_s, is estimated to be approximately 0.05 to 0.1 sec.

The results of evaluating the relations for τ_c, τ_q and τ_s is that τ_c and τ_s operate on comparable time scales and that on these time scales the wave potential has grown to sufficient levels to produce quite rapid quasilinear effects as reflected by the small values of τ_q at times on the order of τ_c or τ_s.

In Figure 2, the results of evaluating the equation below are shown

$$v_\perp(\tau) = v_\perp(0) + \frac{e}{m_b\gamma} E_{\perp o} (e^{\gamma t} - 1) \tag{20}$$

where $E_{\perp o}$ is the thermal level of the perpendicular electric field. In this figure plots are made for $\gamma \sim 2\omega_{ci}$ and $\gamma \sim 3\omega_{ci}$. They indicate that $v_\perp(t)$ will reach magnitudes large enough to remove the debris from the loss cone region on the time scale of the estimated saturation time, τ_s. From Figure 2, it can be seen that although the third harmonic wave begins at a lower fluctuation level, due to its faster growth rate, it reaches levels of sufficient size to cause the pitch angle scattering more rapidly than the second harmonic. It is expected that waves with faster growth rates would continue this trend.

Both the second and third harmonic waves appear in Figure 2 to produce sufficient pitch angle scattering to explain the second brightening phenomena. The estimates indicate that the time scales for the wave to grow and reach at least saturation amplitudes are faster than the pulse width of debris.

DISCUSSION

Due to the very complicated relations between the wave dispersion relations and the beam distribution function in this calculation and the lack of knowledge about the details of the time evolution of the debris spectrum, it is impossible to make statements concerning the exact region of the debris distribution function which will excite the waves. Estimates can be made, however, which will indicate probable areas of interest.

Before these estimates can be made some details of the wave dispersion relation must be presented. It was found during the numerical calculation that the frequency at any $k_\perp$ valid with the parameter regime of the calculation was independent of $k_{||}$. It was also found in this same parameter regime that the frequency was slowly varying in $k_\perp$. Therefore, to good accuracy over the full range of possible $v_{b||}$ one could consider the frequency shift, $\omega - \ell\omega_{ci}$, to be a constant.

During the course of the calculation it was found that the modes that could be excited had a very limited range in $k_{||}$ and that this preferred parallel wavelength was about 30 km. To some extent this particular wavelength is a function of the distribution used but the narrowness of the spectrum is probably independent of it. As can be seen in Figure 1, there was a fair range of $v_{||}$ space in which the distribution had a positive slope but the modes discussed here were the only ones undergoing energy transfer. Using the resonant condition for beam wave energy transfer, $v_{b||} = (\omega - \ell\omega_{cb})k_{||}$, and noting that the scale height of the atmosphere may limit the length of any given mode, one can estimate an upper bound on the parallel velocity which might

excite waves. With the scale height $\sim$100 km and recalling the $\omega - \ell\omega_{cb} \sim$ constant the maximum parallel beam velocity is estimated to be about 2.3×10^8 cm/sec. At equatorial latitudes the scale height argument does not apply and one may find longer wavelengths thus higher parallel velocities. One can make additional estimates by noting that the mode which appears to be the most unstable in this sample calculation has a parallel wavelength of about 30 km and that the correlation time, where $\tau_c \sim \Delta v_{b||}/(v_{b||}\delta\omega)$, has a range of about 0.025 sec to 0.1 sec. With these parameters the range of velocities which might excite the waves is found to be about 6×10^7 cm/sec to 1.2×10^8 cm/sec. However, once the waves have been excited debris of all velocities would undergo strong pitch angle scattering. Clearly particles with higher velocities than those exciting the wave would also be scattered by these waves but the proportion of particles scattered at any given energy would be lower. This occurs because the high energy particles emitted from the coupling shell at the earliest times would encounter low levels of wave turbulence while high energy particles emitted later would see high fluctuation levels. The exact timing of such occurrences is difficult to ascertain.

The time of arrival for the particles with velocities in the range 6×10^7 to 2.3×10^8 cm/sec is the southern conjugate region (SCR) can be easily estimated. Using 4000 km as a canonical distance, one finds that these particles will arrive in the SCR in the time frame of 1.8 to 7 sec. However, since these particles are expected to excite the waves they represent the sections of the distribution which will be most drastically isotropized by the waves. This would remove as much as 50% of the debris population in this velocity range from the loss cone and would account for the second brightening .

While this discussion has been directed toward specific set of Bernstein modes, one could expect a spectrum of both varying wavelengths and different frequency harmonics to be excited. The higher harmonic modes, $\ell > 2$, would be excited by the faster portions of the streaming debris and will be scattered by these modes. The fluctuation levels may be expected to be less than the modes discussed at length here due to energy coupling difficulties encountered by the higher harmonic modes.[1] In any case the range of the spectrum will be greatly effected by the exact details of the debris distribution as a function of time and space. As a final comment estimates made from the SCORPIO code runs indicate that there would be sufficient beam density to excite these waves in the parameter region discussed.

CONCLUSIONS

The results of the linear calculations indicate that the ion Bernstein modes near the second and third harmonic of the plasma cyclotron frequency will be excited by the streaming debris. Modes of higher frequency may also be excited but were not considered in these calculations.

Quasilinear estimates indicate that quasilinear effects will occur on time scales shorter than the debris pulse width $\sim$1 sec. Using simple estimates for the growth rates and the amplitude of the perpendicular electric field as a function of time, it is found that considerable diffusion of the debris distribution function will occur on time scales comparable with the saturation time, i.e., $\sim$0.1 sec.

The pitch angle scattering predicted from the quasilinear estimates is more than sufficient to remove a significant fraction of the streaming debris particles from the loss cone. From the estimates made of the range of possible beam velocities that might excite the wave and undergo pitch angle scattering it was found that a large percentage of the total debris distribution was susceptible to these instabilities.

The estimates appear to be in agreement with the data in the SCR. The second brightening in this region appeared to be nearly as bright as the first indicating something approaching equal partition of the energy between the two depositions. From these calculations most of the debris distribution would be susceptible to the instabilities and one then has the possibility of up to 50% of the debris being mirrored. This of course would be the upper bound and a more realistic number probably involves factors of two. An additional phenomena was observed during

the SCR deposition. It appeared on the film that the altitude of deposition between the first and second brightening had changed. The region of luminescence caused by the second deposition appeared at a higher altitude. These results would indicate that the energy of the most energetic particles in the debris being deposited was less than at the time of the first deposition. This again appears to be consistent with the effects of the instability. As the waves are excited, the particles must lose energy. This would have the effect of decreasing the energy of the portions of the distribution which is exciting the waves. Typically the higher energy particles.

In summary, from the linear and quasilinear calculations it is certain that the ion Bernstein waves can be excited. It appears that they can be excited to sufficient wave amplitude to cause strong pitch angle scattering and explain the second brightening seen in the southern conjugate region during the Starfish event. It also seems clear that nonlinear effects may make the phenomena discussed here even more pronounced if flattening of the distributions occurs. This flattening would inhibit the excitation of these waves after the isotropization. The result of this would be that upon subsequent bounces the particles would not be scattered out of the loss cone by these instabilities and would then precipitate for the most part upon return to the SCR, with particles being returned to the loss cone region by loss cone instabilities. Work on a problem similar to this is discussed in References 13 and 14 where the authors have addressed the problem of electron trapping in the radiation belts.

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Table I

Input Parameters for Ion Bernstein Mode

Electron Temperature	0.07 eV
Ion Temperature	0.07 eV
Magnetic Field	0.3 G
Electron Density	$1.0 \times 10^4/cm^3$
Mass of Beam Particle	27 m_p
Beam Density	0.2 n_e
Mass of Background Ions	16 m_p
Initial Beam Velocity	1.18×10^8 cm/sec or 200 keV

Table II

Results for the second Harmonic Excitation

ℓ	$= 2$
Growth Rate ,γ,	$\leq 2\omega_{ci}$
$\omega - \ell\omega_{ci}$	$\sim 0.01\omega_{ci} \rightarrow 0.01 \quad _{ci}$
ω_{ci}	$\sim 1.80 \times 10^{2}$/sec
ω_{cb}	$\sim 1.06 \times 10^{2}$/sec
ω	$\sim 3.56 \times 10^{2}$/sec
$k_{\perp}$	$\sim$ 1.E-6/cm
$k_{\|\|}$	$\sim$ 2.E-6/cm
v_{thi}	$\sim 9.15 \times 10^{4}$ cm/sec
$v_{g\perp}$	$\sim 2.97 \times 10^{2}$ cm/sec
$v_{g\|\|}$	$\sim 1 \times 10^{7}$ cm/sec

Table III

Parameter for Quasilinear Estimate

$\Delta v_{b\perp}$	$\sim$	$v_{b\perp} \sim \ell\omega_{cb}/k_{\perp}$
$\Delta v_{b\|\|}$	$\sim$	$0.2 v_{b\|\|}$
$v_{b\perp}$	$\sim$	$0.1 v_{b\|\|}$
$\Delta k_{\|\|}$	$\sim$	3×10^{-7}/cm
$\Delta k_{\perp}$	$\sim$	3×10^{-6}/cm
$J_{\ell}(b)e^{-b}$	$\sim$	$(b/2)^{\ell} e^{-b} \sim (b/2)^{\ell}$
$J_{\ell}(k_{\perp} v_{\perp}/\omega_{cb})$	$\sim$	$(1/2\ k_{\perp} v_{\perp}/\omega_{cb})^{\ell}$
$\Delta^3 k$	$\sim$	$\Delta k_{\|\|} \Delta k_{\perp}^2$
c_s	$\sim$	6.47×10^5 cm/sec
v_b	$\sim$	1.18×10^8 cm/sec

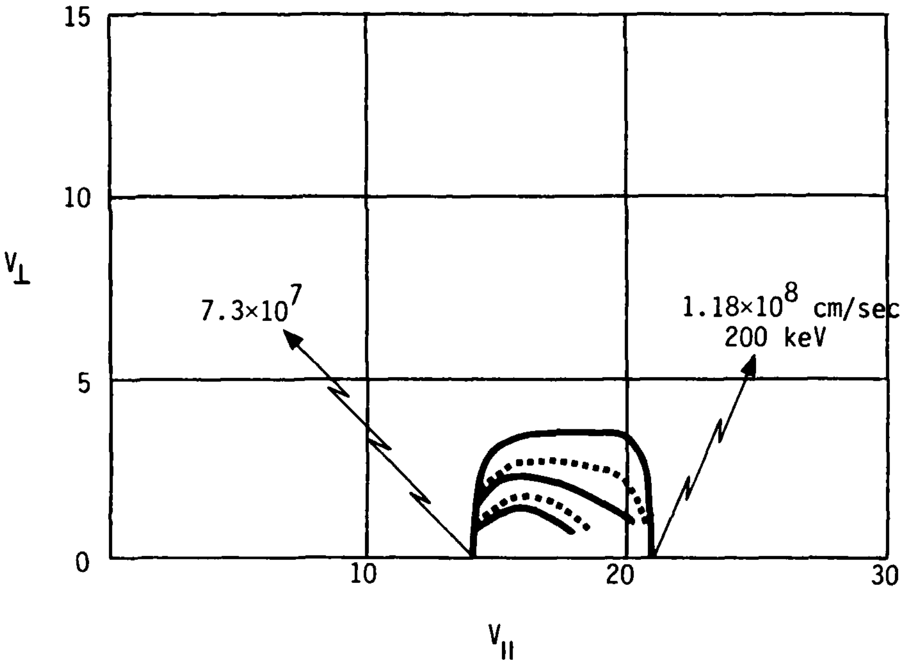

Figure 1

The debris distribution functions as used in the linear calculation. The velocity of injection is 1.18×10^8 cm/sec. The velocities on the plot are in dimensionless units. The normalization velocity is 5.59×10^6 cm/sec.

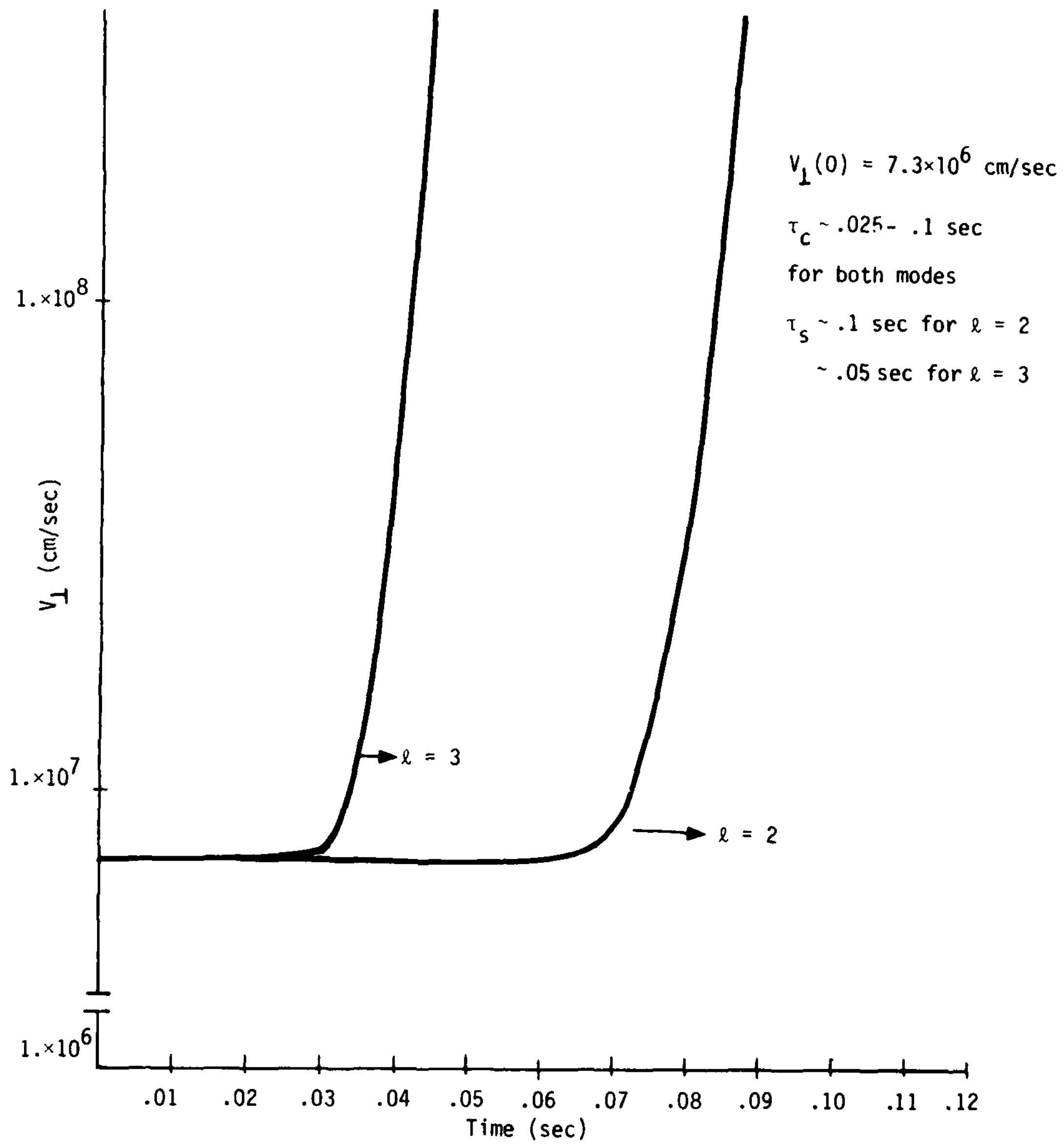

Figure 2

The time evolution of the perpendicular velocity of the streaming debris. The initial $v_{b\perp}$ is assumed 0.1 of $v_{b||}$. The parallel correlation time, τ_c, and τ_s, the estimated time for parallel trapping effects are shown for each mode. In both $\ell = 2$ and $\ell = 3$ case it was assumed that $\gamma \sim \ell\omega_{ci}$.

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